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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 822

TANDEM AIR PROPELLERS - II

By E. P. Lesley
Daniel Guggenheim Aeronautical Laboratory
Stanford University

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 822

TANDEM AIR PROPELLERS - II

By E. P. Lesley

SUMMARY

Tests of three-blade, adjustable-pitch counterrotating tandem model propellers, adjusted to absorb equal power at maximum efficiency of the combination, were made at Stanford University.

The aerodynamic characteristics, for blade-angle settings of 15°, 25°, 35°, 45°, 55°, and 65° at 0.75R of the forward propeller and for diameter spacings of $8\frac{1}{2}$, 15, and 30 percent were compared with those of three-blade and six-blade propellers of the same blade form.

It was found that, in order to realize the condition of equal power at maximum efficiency, the blade angles for the rear propeller must be generally less than that for the forward propeller, the difference increasing with blade angle.

The tests showed that, at maximum efficiency, the tandem propellers absorb about double the power of three-blade propellers and about 8 percent more power than six-blade propellers having the pitch of the forward propeller of the tandem combination.

The maximum efficiency of the tandem propellers was found to be from 2 to 15 percent greater than for six-blade propellers, the difference varying directly with blade angle. It was also found that the maximum efficiency of the tandem propellers was greater than that of a three-blade propeller for blade angles at 0.75R of 25° or more. The difference in maximum efficiency again varied directly with blade angle, being about 9 percent for 65° at 0.75R.

INTRODUCTION

Tests of two-blade oppositely rotating tandem propellers were carried on at Stanford University in 1918 (reference 1). The results were not promising. It was found that the efficiency of the combination was less than that of a single two-blade propeller. Although no tests of four-blade propellers were made at the time, it now appears that the tandem propellers showed little, if any, greater efficiency than would be expected for four-blade propellers of similar form designed to absorb the same power. It was also found that, in the region of maximum efficiency, the torque of either propeller was reduced when the other developed thrust. The maximum pitch-diameter ratios employed in these tests was 0.9, which corresponds to a blade angle of 21° at 75 percent of the tip radius (0.75R).

At about the same time, Lanchester showed that tandem propellers might develop considerably greater efficiency than a single propeller, particularly for pitch-diameter ratios as great as 2 or possibly 3 (reference 2).

A second experimental study of this subject was made at Stanford in 1938 (reference 3). It was shown that, compared with four-blade propellers absorbing about the same power, the tandem propellers developed the higher efficiency. The gain in efficiency was found to be more pronounced for the propellers of large blade angles, being about 0.005 for 15° at 0.75R and 0.015 for 45° at the same station. It was also found that, for the largest blade angle investigated, 45° at 0.75R, the tandem propellers were slightly superior in efficiency to a single two-blade propeller. In view of the promising results of these tests, particularly for the higher blade angles, the subsequently described investigation was carried on at the request and with the financial assistance of the National Advisory Committee for Aeronautics.

The tests reported in reference 3 indicated an efficiency advantage for tandem propellers that varied directly with blade angle. It was therefore presumed that greater blade angles would show greater advantages. For the airplane speeds now commonly attained, greater blade angles than those employed in the previous tests might be desirable and, for speeds of 400 to 500 miles per hour and for permissible resultant tip speeds, blade angles as great as 65° might be required. The range of blade angles employed in the present investigation was therefore extended to include 65° at 0.75R. Three blade units were chosen for the tandem combination and a six-blade propeller for comparison with it.

The condition selected for the tandem propeller tests was that the powers absorbed by the two propellers should be equal at maximum efficiency. Since the angular velocities were equal, this condition provided that there would be balanced torque and a slipstream, on the average, free from rotation.

APPARATUS AND TESTS

Wind tunnel.- The experiments were carried on in the wind tunnel of the Daniel Guggenheim Aeronautic Laboratory at Stanford University. The tunnel is of the Eiffel type with open throat, $7\frac{1}{2}$ feet in diameter. The maximum wind velocity is 90 miles per hour.

Dynamometer.- The model propeller dynamometer has been described in reference 3. It provides for measurement of torque on the two propellers independently so that the difference in power absorbed as well as the total may be determined. Only the total thrust is measured.

Model propellers.- The right- and the left-hand three-blade propellers for the tandem combination were three-foot-diameter, metal, adjustable-pitch models of standard U. S. Navy plan form and blade sections. The geometrical pitch-diameter ratio, for a blade angle of 16.6° at 0.75R, was 0.7 from 0.6R outward to the tip. The pitch-diameter ratio gradually decreased toward the hub from 0.6R to 0.42 at 0.15R. Dimensioned drawings and section ordinates of the blades (designated E) are given in reference 4.

In the six-blade propeller, in order to provide sufficient room for the blade-clamping device, the hub was made 1 inch greater in diameter than the three-blade hubs. The blades were thus set out $\frac{1}{2}$ inch, making the propeller 37 inches in diameter. As a result, there were slight differences in pitch-diameter, width-diameter, and thickness-width ratios as functions of the ratio of station radius to tip radius (r/R) for the three-blade and the six-blade models, as shown in figure 1. While these differences might conceivably have some effect on comparative tests of three-blade and six-blade propellers, it is believed that such an effect would be insignificant in comparison with the effect of difference in solidity. The appearance of the propellers, when mounted on the dynamometer ready for test, is shown in figures 2 and 3.

Tests.- Tests were made of each propeller alone, three-blade right-hand, three-blade left-hand, and six-blade, for blade angles of 15°, 25°, 35°, 45°, 55°, and 65° at 0.75R. Tests of the tandem propellers were made with the forward (right-hand) propeller also set at these blade angles but with the rear (left-hand) propeller adjusted to absorb the same power as the forward propeller at maximum efficiency of the combination. For the 25° blade angle of the tandem propellers, three axial spacings were employed, 8½ percent, 15 percent, and 30 percent of the diameter, from center to center of the blade shanks. Other tandem-propeller tests were made at the 15-percent-diameter spacing only.

Constant angular velocities were used for each blade angle, variation in the parameter V/nD (pitch-diameter ratio) being secured through change of the wind velocity. Because of limitations imposed by maximum wind speed and by power and rotational speed available in the dynamometer, the rotational speeds employed were 2100, 2100, 1575, 1150, 900, and 650 rpm for the 15°, 25°, 35°, 45°, 55°, and 65° blade angles, respectively. The Reynolds number of the tests thus varied from 0.116 to 0.036 full scale, assuming full-scale propellers 9 feet in diameter turning at 2000 rpm. The test data were reduced to the coefficient form:

Thrust coefficient, $C_T = \dfrac{T}{\rho n^2 D^4}$

Power coefficient, $C_P = \dfrac{P}{\rho n^3 D^5}$

Efficiency, $\eta = \dfrac{TV}{P} = \dfrac{C_T}{C_P}\ \dfrac{V}{nD}$

Speed power coefficient, $C_s = \sqrt[5]{\dfrac{\rho V^5}{Pn^2}} = \dfrac{V}{nD}\sqrt[5]{\dfrac{1}{C_P}}$

where T propeller thrust

ρ mass density of the air

n revolutions per unit time

D propeller diameter

P power absorbed

V velocity

RESULTS AND DISCUSSION

The difference in blade angle required to meet the condition of balanced torque at maximum efficiency of the tandem propellers is shown in figure 4. It agrees closely, possibly within the error of measurement, with that found in reference 3. The conclusion reached in reference 1, that to absorb equal power the two propellers should have the same pitch-diameter ratio, appears to have been not far wrong for the blade angles employed, 12° to 21°.

That the difference should vary directly with blade angle might have been predicted. From momentum theory, the forward propeller induces increments to the velocity of the air stream acting on the rear propeller. The axial increment, induced by thrust, decreases the angles of attack of the rear propeller blades. The circumferential increment, induced by torque, increases the angles of attack. From blade-element theory, thrust varies inversely and torque directly with blade angle. Therefore, as the blade angle of the forward propeller is increased, the angles of attack of the rear propeller tend to become progressively greater and its blade angle must be reduced to realize the condition of balanced torque. It further seems quite possible that, at the 15° blade angle, the axial increment of velocity is great enough to more than overcome the effect of the circumferential increment. The rear propeller blades must thus have a greater angle for balanced torque, as shown.

Variation in axial spacing of tandem propellers is found to have a minor effect on performance. Figure 5 shows the results of tests for the 25° blade angle. It may be seen that, for continued balanced torque, the blade angle of the rear propeller is increased somewhat as the spacing becomes greater. The thrust and power coefficients also vary slightly and directly with axial spacing. This variation is perhaps little more than would be expected from the change in blade angle of the rear propeller. Similar results were derived from the tests of reference 3.

The apparent effect of spacing on efficiency is extremely small, but that indicated by the present tests is opposite to that shown in reference 3. In either case, however, the change in maximum efficiency, presumably brought about by variation in spacing, is less than 1 percent. Since the effects are small and inconsistent, they may be attributed to experimental error. As evidenced by consecutive tests of a single propeller, the probable error in maximum efficiency is about 0.005.

The test data for right-hand three-blade, six-blade, and tandem propellers are given in tables I, II, and III. For the tandem propellers, C_P and C_s are coefficients computed for the total power absorbed and C_T a coefficient for total thrust. The values in the column headed C_P(RH-LH) are the difference in power coefficients of the forward (right-hand) and rear (left-hand) propellers.

In figures 6, 7, and 8, C_P, C_T, and η are represented as functions of V/nD. In these figures, logarithmic scales are employed, which permits showing small and large numerical values of the data with equal relative accuracy and, at the same time, keeps the diagrams within moderate size. These figures were prepared by plotting the tabular to arithmetical scales, drawing representative curves, and taking off values of C_T, C_P, and η at convenient points. If plotted, points will be found to lie, with few exceptions, upon or very close to the curves shown. Design charts for the selection of three-blade, six-blade and tandem propellers are shown in figures 9, 10, and 11.

Graphical and tubular data for the three-blade left-hand propellers are, in the interest of brevity, omitted from this report. It was found that the results of tests of right-hand and left-hand propellers were, within the limits imposed by probable errors in blade angles and in experimental observations, substantially the same. The probable error in blade angle is $\pm 0.1^\circ$. Because of possible inclination of the mandrel on which the propellers were placed for blade-angle adjustment and measurement, the error may have been of one sign for the right-hand propellers and of the opposite sign for the left-hand propellers. A difference in blade angle of 0.2° is sufficient to account for the greater part of the disagreement in results of tests.

Figure 12 shows the effect of each propeller of the tandem combination upon the power absorbed by the other at maximum efficiency (η_{max}). For the forward propeller, the effect shown was derived by direct comparison of the C_P for that propeller when alone with the C_P when in the tandem combination. In the second case, C_P is generally one half the C_P for the tandem propellers as a whole since, at maximum efficiency, the torque was balanced as nearly as practicable. For the rear propeller, it was necessary to interpolate power coefficients for the propeller alone because generally that propeller was tested alone only at the same blade angles as the forward propeller. A check test for the rear propeller at 53.1° was made. The coefficients agreed closely with those derived by interpolation.

Figure 12 shows that the rear propeller has a negligible effect on the power absorbed by the forward propeller for blade angles greater than 25°. At lower blade angles, the power absorbed by the forward propeller is decreased by the action of the rear propeller. For the rear propeller, the power absorbed is greatly increased by the forward propeller at the largest blade angle and reduced by about the same amount at the smallest blade angle. This figure is effectively in agreement with figure 4. It also bears out the conclusion of reference 1 that, for blade angles of 21° and less, the power absorbed by either propeller is reduced by the presence of the other.

A summary of performance characterics at maximum efficiency for three-blade, six-blade, and tandem propellers is shown in figure 13. It is evident from this figure that, for blade angles above 25°, the power absorbed by the tandem propellers is about twice that absorbed by a single three-blade propeller of the same size. For blade angles less than 25°, there is a marked reduction of the ratio. The tandem propellers absorb an average of 8 percent more power than six-blade propellers of equal size.

For all blade angles, the tandem propellers have greater maximum efficiency than six-blade propellers. The difference varies directly with blade angle and becomes about 15 percent at 65°. For blade angles above 25°, the maximum efficiency of tandem propellers is greater than that of single three-blade propellers. The difference again varies directly with blade angle and is about 9 percent at 65°. For blade angles less than 25°, the tandem propellers show less maximum efficiency than three-blade propellers.

The relation of the maximum efficiency curves for three-blade and tandem propellers may be predicted. The difference in maximum efficiency at the 15° blade angle is less than the difference in ideal efficiency of momentum theory. The rotational energy in the slipstream of the three-blade propeller set 15° is small and therefore little is to be gained through even complete conservation, as shown by Lanchester in reference 2. On the other hand, the difference in ideal efficiency for the 65° blade angle is one-fourth that for the 15° blade angle. The rotational energy of the slipstream of the three-blade propeller set 65° is manyfold greater. Even partial conservation may therefore result in considerably improved efficiency.

Calculations for efficiency, based on combined blade element and momentum theories, yielded results qualitatively in agreement with tests, but the differences found were less than those shown in figure 13. A source of relative efficiency for the rear propeller that was greater than claculated may be Katzmayr effect. The rear propeller blades move in a wind stream of variable velocity and direction induced by the forward propeller. It has been shown that, in an oscillating wind stream, the drag of an airfoil, referred to the mean direction of flow, becomes smaller and may even be negative (reference 5). This effect would increase the computed relative efficiency of the rear propeller and thus that of the tandem combination.

Figures 10 and 11 show, as would be expected from figure 13, greater efficiency for tandem propellers than for the six-blade propeller at all values of C_s. Figures 9 and 11 indicate greater efficiency for tandem propellers than for three-blade propellers at values of C_s greater than about 1.3. For equal power, revolution speed, and velocity (equal C_s), the diameter and hence the tip speed will be greater for three-blade propellers than for tandem propellers. Tip speed may affect efficiency. It therefore seems that a more logical basis for comparison of efficiency than at equal values of C_s is at equal velocities of advance and tip speeds, or at equal values of V/nD. The V/nD for equal maximum efficiency of three-blade and tandem propellers is about 0.85. For greater values of V/nD, tandem propellers have the greater maximum efficiency. For a resultant tip speed of 1000 feet per second, the velocity of advance at $V/nD = 0.85$ is about 180 miles per hour. For lower tip speeds, the velocity of advance is proportionally reduced. It may be thus seen that tandem propellers will have, at permissible tip speeds, greater efficiency than three-blade propellers at velocities of advance in excess of 180 miles per hour.

Tandem propellers appear to give no promise of improved airplane performance at velocities below 180 miles per hour unless the tip speeds are less than 1000 feet per second. They should have, however, particularly in the estimation of the airplane pilot, two incidental advantages that may compensate for a small loss of efficiency at low speed. These are: (1) improvement in longitudinal control through elimination of rotation from the air stream which acts upon the tail surfaces; and (2) improvement in lateral control through removal of rolling moment due to unbalanced torque.

Tandem propellers may possibly result in a decrease of weight-power ratio from that attainable with single propellers. It may be assumed that the tandem propellers would have twice the weight of three-blade propellers of the same size and that the weight of similar propellers varies as the cube of their linear dimensions. If these assumptions are tenable, the weights of tandem and three-blade propellers for equal power and at equal tip speeds will be in the ratio of 1 to $\sqrt{2}$.

Aside from design of pitch-control mechanism, tandem propellers appear to present but two possible difficult problems: elimination of noise and of danger from structural failure.

The rear propeller blades especially, as they pass through an air stream of variable velocity and direction, produce noise. The frequency of the sound waves is, for equal rotational speeds of three-blade tandem propellers, 6 n. The intensity and the volume of the sound depends upon the violence of velocity and directional changes encountered by the blades and upon the amplitude of the vibrations induced in them.

In the present model tests, the noise of the tandem propellers was most noticeable at the higher rotational speeds used for the smaller blade angles. If the volume of sound should increase continuously with scale, the noise of tandem propellers may constitute an objectional feature in flight.

It is obvious that, because of variation in load, forced vibrations of the same frequency as that of the sound waves will be impressed upon the propeller blades. If this frequency is equal or close to that for some mode of elastic vibration of the blade itself, there will be increased amplitude of vibration with resultant stresses possibly greater than allowable.

Although there was no evident blade flutter during the model-propeller tests, it is believed this problem may be serious in full-scale operation. The frequency for the first mode of vibration for the model blades was found, by experiment, to be about 90 cycles per second. The frequency for the second mode was estimated to be about 560 cycles per second. For geometrically and elastically similar blades, the frequency of vibration varies inversely as the linear dimensions, and thus the frequency for the second mode of vibration of a 9-foot propeller would be 186 cycles per second. At 1860 rpm, however, the frequency of forced vibration of three-blade tandem propellers will also be 186 cycles per second.

The frequency of elastic vibrations will be increased, in rotation, by the stiffening effect of centrifugal force. It appears that, for full-scale propellers of similar form and material to the models, the frequency for the second mode of elastic vibration may be dangerously near that of the forced vibrations. In any event, it seems that the possible effect of synchronous forced and elastic vibrations in proposed installations of tandem propellers should be investigated.

CONCLUSIONS

These tests have shown that, for blade angles of 15° to 65° at 75 percent of the tip radius (0.75R), identical, counterrotating, three-blade, closely spaced tandem propellers, adjusted to absorb equal power at maximum efficiency, have from 2 percent to 15 percent greater efficiency than that of six-blade propellers of similar blade form.

Tandem propellers have lower maximum efficiency than single three-blade propellers for blade angles at 0.75R less than 25°. For larger blade angles, the tandem propellers have an increasing advantage which becomes about 9 percent at 65°.

Tandem propellers absorb, respectively, about 8 and 100 percent more power than six-blade and three-blade propellers of equal size.

Daniel Guggenheim Aeronautical Laboratory,
Stanford University, September 20, 1939.

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TABLE I

Three-Blade Right-Hand Propeller

15° at 0.75 R				
V/nD	C_T	C_P	C_s	η
0.734	0.0020	0.0120	1.780	0.122
.679	.0178	.0204	1.478	.592
.631	.0292	.0266	1.304	.695
.593	.0379	.0307	1.191	.732
.548	.0483	.0356	1.089	.745
.506	.0576	.0394	.966	.739
.473	.0646	.0422	.891	.724
.425	.0748	.0452	.790	.703
.370	.0833	.0473	.681	.651
.326	.0908	.0485	.597	.607
.254	.1007	.0497	.468	.514
.202	.1058	.0493	.369	.433
.145	.1124	.0491	.261	.327

TABLE I

Three-Blade Right-Hand Propeller

25° at 0.75 R				
V/nD	C_T	C_P	C_s	η
1.166	0.0024	0.0216	2.611	0.150
1.123	.0174	.0349	2.198	.540
1.059	.0316	.0478	1.946	.700
1.007	.0457	.0598	1.770	.770
.963	.0549	.0675	1.651	.784
.912	.0638	.0732	1.540	.797
.868	.0735	.0795	1.442	.800
.817	.0819	.0846	1.359	.791
.783	.0888	.0886	1.272	.785
.738	.0962	.0921	1.190	.771
.689	.1049	.0959	1.102	.754
.638	.1135	.0997	.996	.727
.588	.1215	.1011	.925	.704
.541	.1279	.1021	.854	.677
.479	.1344	.1042	.753	.617
.419	.1375	.1068	.659	.554
.354	.1374	.1098	.551	.445
.312	.1376	.1098	.486	.391
.265	.1375	.1116	.411	.326

TABLE I

Three-Blade Right-Hand Propeller

35° at 0.75 R				
V/nD	C_T	C_P	C_s	η
1.625	0.0172	0.0613	2.840	0.457
1.586	.0300	.0778	2.642	.612
1.523	.0449	.0964	2.451	.709
1.468	.0556	.1083	2.290	.752
1.409	.0668	.1200	2.152	.784
1.361	.0760	.1278	2.053	.809
1.297	.0868	.1387	1.926	.812
1.231	.0972	.1481	1.805	.808
1.171	.1069	.1554	1.700	.805
1.111	.1168	.1624	1.598	.798
1.051	.1253	.1667	1.506	.777
.999	.1290	.1720	1.421	.749
.939	.1298	.1770	1.328	.689
.880	.1316	.1781	1.243	.650
.801	.1333	.1798	1.128	.594
.728	.1358	.1836	1.022	.538
.646	.1383	.1850	.905	.483
.582	.1402	.1870	.813	.436
.497	.1443	.1914	.691	.375
.414	.1484	.1952	.573	.315

TABLE I

Three-Blade Right-Hand Propeller

45° at 0.75 R				
V/nD	C_T	C_P	C_s	η
2.247	0.0378	0.1380	3.340	0.615
2.188	.0485	.1554	3.174	.683
2.103	.0626	.1775	2.971	.742
2.025	.0753	.1962	2.802	.777
1.944	.0876	.2137	2.647	.797
1.856	.0997	.2291	2.491	.807
1.763	.1120	.2439	2.340	.810
1.681	.1221	.2557	2.210	.803
1.599	.1298	.2648	2.087	.784
1.511	.1315	.2689	1.966	.739
1.420	.1319	.2676	1.850	.700
1.335	.1328	.2674	1.739	.662
1.251	.1337	.2679	1.641	.630
1.181	.1356	.2681	1.538	.597
1.112	.1369	.2694	1.448	.566
1.045	.1385	.2706	1.356	.534
.962	.1401	.2728	1.275	.504
.874	.1425	.2775	1.130	.449
.790	.1455	.2828	1.017	.406
.694	.1465	.2905	.888	.350
.567	.1503	.2980	.723	.286

TABLE I

Three-Blade Right-Hand Propeller

55° at 0.75 R				
V/nD	C_T	C_P	C_s	η
2.925	0.0866	0.3594	3.593	0.705
2.863	.0942	.3721	3.494	.725
2.783	.1024	.3870	3.365	.737
2.704	.1107	.3991	3.250	.750
2.640	.1184	.4111	3.155	.760
2.566	.1254	.4200	3.050	.766
2.506	.1317	.4282	2.962	.769
2.426	.1371	.4361	2.861	.762
2.369	.1402	.4392	2.790	.756
2.291	.1415	.4414	2.699	.735
2.223	.1415	.4392	2.620	.717
2.159	.1412	.4337	2.547	.703
2.077	.1404	.4259	2.460	.684
2.013	.1395	.4210	2.394	.668
1.926	.1375	.4135	2.299	.641
1.865	.1368	.4086	2.232	.62[illegible]
1.784	.1358	.4028	2.142	.608
1.730	.1354	.4001	2.079	.586
1.658	.1345	.3953	1.995	.564
1.587	.1335	.3940	1.910	.538
1.527	.1335	.3912	1.842	.521
1.467	.1327	.3886	1.772	.502
1.381	.1329	.3873	1.670	.474
1.295	.1331	.3886	1.563	.443
1.193	.1338	.3898	1.441	.410
1.065	.1352	.3951	1.283	.365
.941	.135[illegible]	.3968	[illegible].132	.322
.814	.1348	.3967	.979	.277

TABLE I

Three-Blade Right-Hand Propeller

65° at 0.75 R				
V/nD	C_T	C_P	C_s	η
4.060	0.1264	0.808	4.240	0.640
3.938	.1351	.808	4.109	.658
3.869	.1391	.812	4.031	.663
3.800	.1435	.814	3.954	.670
3.728	.1485	.816	3.880	.679
3.680	.1520	.819	3.828	.683
3.606	.1560	.820	3.751	.686
3.540	.1600	.821	3.677	.689
3.480	.1622	.820	3.619	.689
3.413	.1647	.815	3.553	.690
3.330	.1651	.808	3.474	.681
3.259	.1636	.801	3.403	.666
3.203	.1616	.791	3.360	.654
3.120	.1592	.778	3.282	.644
3.049	.1561	.752	3.231	.633
2.966	.1516	.729	3.163	.617
2.861	.1473	.773	3.072	.600
2.800	.1433	.685	3.023	.586
2.699	.1380	.660	2.933	.565
2.609	.1339	.638	2.852	.548
2.512	.1302	.619	2.763	.528
2.466	.1275	.608	2.720	.517
2.403	.1249	.597	2.667	.503
2.300	.1202	.572	2.572	.484
2.217	.1142	.556	2.492	.455
2.127	.1127	.547	2.399	.438
2.065	.1108	.541	2.333	.423
1.952	.1078	.529	2.212	.398
1.804	.1047	.520	2.058	.363
1.675	.1019	.515	1.913	.331
1.550	.1010	.512	1.703	.306
1.368	.1005	.505	1.570	.272
1.196	.1000	.503	1.368	.238
987	.1000	.500	1.131	.197

TABLE II

Six-Blade Right-Hand Propeller

15° at 0.75 R				
V/nD	C_T	C_P	C_s	η
0.695	0.0216	0.0322	1.379	0.465
.642	.0437	.0446	1.196	.629
.594	.0630	.0544	1.065	.688
.545	.0794	.0681	.946	.694
.495	.0960	.0692	.844	.686
.458	.1077	.0738	.771	.668
.416	.1198	.0765	.692	.656
.372	.1314	.0822	.613	.594
.343	.1386	.0844	.562	.563
.297	.1494	.0873	.484	.508
.258	.1574	.0887	.419	.458
.192	.1707	.0916	.310	.358

TABLE II

Six-Blade Right-Hand Propeller

25° at 0.75 R				
V/nD	C_T	C_P	C_s	η
1.099	0.0391	0.0719	1.860	0.598
1.067	.0551	.0864	1.742	.681
1.025	.0722	.1008	1.680	.733
.976	.0894	.1147	1.606	.760
.928	.1052	.1277	1.402	.764
.883	.1185	.1375	1.315	.761
.836	.1347	.1479	1.227	.761
.788	.1485	.1561	1.145	.749
.742	.1625	.1646	1.064	.733
.689	.1777	.1725	.979	.709
.638	.1897	.1779	.902	.680
.585	.2023	.1825	.822	.648
.535	.2138	.1858	.749	.616
.490	.2271	.1889	.669	.577
.448	.2331	.1901	.620	.546
.382	.2400	.1945	.530	.471
.305	.2411	.2029	.419	.362
.201	.2443	.2062	.276	.238

TABLE II

Six-Blade Right-Hand Propeller

35° at 0.75 R				
V/nD	C_T	C_P	C_s	η
1.589	0.0655	0.1433	2.348	0.615
1.543	.0751	.1682	2.202	.689
1.512	.0861	.1807	2.130	.720
1.481	.0948	.1908	2.060	.736
1.460	.1030	.1994	2.014	.754
1.432	.1119	.2069	1.958	.767
1.402	.1228	.2219	1.893	.776
1.375	.1291	.2286	1.845	.777
1.345	.1408	.2396	1.789	.790
1.314	.1477	.2468	1.737	.786
1.286	.1576	.2567	1.687	.790
1.247	.1666	.2660	1.625	.781
1.221	.1743	.2721	1.585	.782
1.184	.1840	.2806	1.527	.776
1.153	.1927	.2880	1.479	.778
1.120	.2009	.2941	1.432	.764
1.056	.2150	.3038	1.344	.749
.991	.2309	.3132	1.251	.730
.925	.2401	.3233	1.160	.687
.855	.2354	.3251	1.071	.621
.724	.2400	.3300	.905	.526
.518	.2520	.3438	.642	.380
.388	.2567	.3512	.478	.283
.241	.2546	.3578	.296	.172

TABLE II

Six-Blade Right-Hand Propeller

45° at 0.75 R				
V/nD	C_T	C_P	C_s	η
2.180	0.0918	0.3058	2.767	0.654
2.128	.1060	.3271	2.661	.689
2.099	.1139	.3401	2.607	.702
2.054	.1268	.3560	2.528	.732
2.023	.1354	.3707	2.470	.739
1.968	.1501	.3900	2.377	.757
1.940	.1578	.4044	2.329	.757
1.876	.1729	.4230	2.228	.766
1.811	.1885	.4418	2.132	.773
1.749	.2046	.4590	2.041	.779
1.685	.2167	.4730	1.952	.771
1.644	.2259	.4810	1.899	.772
1.602	.2310	.4892	1.843	.756
1.528	.2369	.5012	1.751	.722
1.444	.2403	.5068	1.650	.685
1.331	.2409	.5087	1.525	.637
1.194	.2440	.5038	1.365	.578
1.087	.2471	.5046	1.244	.532
.936	.2541	.5108	1.069	.466
.756	.2613	.5198	.838	.370
.578	.2648	.5315	.655	.288
.339	.2614	.5315	.384	.167

TABLE II

Six-Blade Right-Hand Propeller

55° at 0.75 R				
V/nD	C_T	C_P	C_s	η
2.882	0.1457	0.662	3.134	0.634
2.817	.1628	.690	3.035	.664
2.776	.1725	.702	2.978	.682
2.735	.1820	.720	2.920	.692
2.697	.1897	.735	2.862	.698
2.647	.1985	.747	2.804	.703
2.592	.2101	.762	2.741	.712
2.516	.2247	.781	2.640	.723
2.470	.2330	.789	2.595	.729
2.443	.2370	.795	2.560	.728
2.410	.2411	.802	2.520	.724
2.367	.2462	.808	2.468	.721
2.312	.2511	.815	2.409	.713
2.247	.2553	.818	2.337	.696
2.202	.2568	.817	2.290	.692
2.178	.2535	.814	2.267	.678
2.105	.2539	.805	2.198	.664
2.036	.2531	.792	2.132	.650
1.962	.2519	.781	2.060	.632
1.889	.2496	.769	1.989	.612
1.822	.2484	.761	1.927	.595
1.760	.2470	.754	1.866	.576
1.689	.2467	.746	1.792	.558
1.621	.2458	.742	1.722	.537
1.564	.2462	.738	1.662	.522
1.489	.2455	.733	1.584	.499
1.385	.2460	.726	1.478	.469
1.138	.2445	.726	1.214	.383
.900	.2436	.729	.953	.303
.661	.2430	.729	.706	.220
.511	.2432	.727	.546	.171

TABLE II

Six-Blade Right-Hand Propeller

65° at 0.75 R				
V/nD	C_T	C_P	C_s	η
3.961	0.2202	1.520	3.648	0.574
3.889	.2323	1.528	3.578	.591
3.807	.2420	1.533	3.499	.600
3.741	.2500	1.535	3.440	.609
3.686	.2554	1.537	3.388	.612
3.620	.2645	1.536	3.328	.624
3.560	.2725	1.536	3.271	.631
3.510	.2754	1.535	3.227	.630
3.434	.2820	1.533	3.158	.632
3.371	.2850	1.527	3.102	.629
3.270	.2872	1.517	3.012	.619
3.200	.2867	1.504	2.950	.609
3.142	.2830	1.481	2.913	.600
3.059	.2800	1.451	2.843	.590
2.992	.2757	1.421	2.791	.580
2.942	.2720	1.397	2.754	.573
2.870	.2647	1.358	2.699	.559
2.820	.2620	1.337	2.660	.552
2.765	.2585	1.303	2.621	.542
2.665	.2478	1.258	2.546	.525
2.579	.2428	1.224	2.479	.512
2.433	.2355	1.169	2.361	.491
2.311	.2296	1.132	2.258	.469
2.211	.2256	1.106	2.170	.451
2.036	.2176	1.061	2.016	.417
1.914	.2123	1.035	1.900	.393
1.689	.2018	1.025	1.683	.332
1.568	.1986	1.007	1.566	.309
1.428	.1942	.996	1.429	.278
1.248	.1875	.972	1.255	.241

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 15° at 0.75 R; Forward

Three-Blade Left-Hand; 15.2° at 0.75 R; Rear

15-Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
0.704	0.0288	0.0351	-0.0030	1.377	0.457
.653	.0438	.0448	- .0024	1.215	.638
.602	.0645	.0556	- .0018	1.072	.698
.557	.0813	.0642	- .0004	.964	.705
.500	.1033	.0744	.0001	.841	.694
.476	.1108	.0773	.0003	.794	.683
.426	.1273	.0843	.0008	.699	.643
.384	.1418	.0887	.0006	.624	.614
.349	.1509	.0918	.0006	.563	.576
.311	.1617	.0959	.0002	.500	.536
.274	.1719	.0964	.0004	.438	.488
.228	.1834	.0982	- .0001	.363	.426
.176	.1940	.0990	- .0009	.280	.345

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 25° at 0.75 R; Forward

Three-Blade Left-Hand; 24.5° at 0.75 R; Rear

8.5 - Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
1.120	0.0366	0.0659	0.0115	1.930	0.622
1.078	.0537	.0839	.0065	1.770	.690
1.037	.0720	.0986	.0039	1.649	.757
.988	.0925	.1152	.0035	1.524	.793
.946	.1080	.1272	.0026	1.431	.803
.898	.1258	.1411	.0025	1.330	.800
.849	.1449	.1545	.0009	1.235	.796
.802	.1590	.1636	.0000	1.152	.779
.755	.1741	.1735	-.0007	1.072	.757
.702	.1887	.1825	-.0017	.986	.726
.652	.2059	.1906	-.0025	.906	.704
.598	.2236	.1982	-.0044	.826	.674
.552	.2353	.2032	-.0047	.759	.639
.490	.2526	.2068	-.0072	.671	.598
.444	.2603	.2102	-.0072	.607	.550
.397	.2707	.2142	-.0090	.540	.501
.305	.2806	.2271	-.0102	.407	.374

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 25° at 0.75 R; Forward
Three-Blade Left-Hand; 24.8° at 0.75 R; Rear
15-Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
1.121	0.0374	0.0701	0.0020	1.908	0.598
1.081	.0550	.0857	.0021	1.767	.694
1.042	.0757	.1034	.0021	1.645	.763
.998	.0935	.1163	.0014	1.536	.802
.947	.1145	.1366	.0010	1.415	.800
.904	.1288	.1457	.0005	1.350	.800
.856	.1453	.1579	.0005	1.259	.788
.806	.1628	.1693	-.0006	1.150	.775
.756	.1782	.1785	-.0013	1.067	.755
.706	.1960	.1888	-.0023	.984	.733
.651	.2112	.1960	-.0029	.902	.705
.601	.2275	.2030	-.0036	.826	.674
.544	.2423	.2078	-.0049	.745	.635
.497	.2543	.2113	-.0067	.678	.598
.449	.2646	.2143	-.0078	.611	.554
.395	.2736	.2193	-.0100	.534	.493
.307	.2780	.2294	-.0123	.412	.372

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 25° at 0.75 R; Forward
Three-Blade Left-Hand; 25° at 0.75 R; Rear
30-Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
1.121	0.0375	0.0712	-0.0026	1.902	0.591
1.070	.0609	.0913	- .0011	1.727	.714
1.028	.0796	.1080	.0008	1.606	.760
.981	.0976	.1215	.0010	1.496	.787
.949	.1129	.1350	.0008	1.418	.794
.899	.1311	.1486	.0005	1.318	.793
.850	.1481	.1614	- .0001	1.225	.780
.803	.1640	.1705	- .0005	1.144	.772
.756	.1810	.1808	- .0009	1.065	.756
.706	.1955	.1896	- .0015	.984	.737
.648	.2132	.1980	- .0025	.896	.698
.594	.2296	.2036	- .0040	.816	.670
.545	.2425	.2094	- .0052	.745	.632
.499	.2545	.2119	- .0066	.681	.599
.449	.2650	.2169	- .0087	.610	.549
.394	.2725	.2270	- .0108	.530	.474
.309	.2768	.2366	- .0137	.412	.361

Table III (cont.)

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 35° at 0.75 R; Forward Three-Blade Left-Hand; 34.3° at 0.75 R; Rear 15-Percent-Diameter Spacing					
V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
1.607	0.0574	0.1458	0.0155	2.365	0.632
1.561	.0804	.1697	.0120	2.227	.740
1.513	.1005	.1931	.0104	2.102	.786
1.443	.1243	.2235	.0070	1.947	.805
1.394	.1421	.2425	.0052	1.851	.818
1.345	.1598	.2620	.0032	1.748	.820
1.278	.1811	.2820	.0011	1.649	.821
1.218	.1992	.2991	-.0009	1.552	.813
1.146	.2198	.3151	-.0032	1.445	.799
1.082	.2388	.3300	-.0045	1.353	.782
1.006	.2588	.3457	-.0066	1.246	.753
.942	.2719	.3562	-.0081	1.159	.719
.866	.2816	.3672	-.0132	1.059	.664
.796	.2860	.3725	-.0191	.972	.611
.715	.2939	.3836	-.0231	.866	.548
.639	.2996	.3925	-.0253	.770	.488
.582	.3043	.3975	-.0267	.700	.446
.490	.3132	.4064	-.0279	.588	.378
.426	.3190	.4145	-.0287	.508	.328

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 45° at 0.75 R; Forward Three-Blade Left-Hand; 43.8° at 0.75 R; Rear 15-Percent-Diameter Spacing					
V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
2.236	0.0867	0.2950	0.0200	2.876	0.680
2.148	.1165	.3331	.0172	2.680	.751
2.081	.1405	.3680	.0136	2.544	.795
2.018	.1599	.3960	.0103	2.428	.815
1.926	.1852	.4325	.0054	2.275	.824
1.861	.2046	.4585	.0005	2.172	.831
1.767	.2304	.4940	-.0041	2.031	.825
1.680	.2520	.5310	-.0068	1.912	.812
1.597	.2790	.5420	-.0106	1.805	.802
1.517	.2845	.5590	-.0127	1.704	.773
1.436	.2933	.5690	-.0198	1.609	.740
1.354	.2982	.5780	-.0257	1.513	.698
1.261	.3014	.5780	-.0295	1.409	.658
1.186	.3080	.5780	-.0324	1.324	.619
1.119	.3040	.5791	-.0339	1.249	.588
1.046	.3070	.5850	-.0360	1.164	.549
.970	.3117	.5915	-.0374	1.077	.511
.868	.3176	.5975	-.0386	.962	.462
.793	.3228	.6020	-.0400	.877	.425
.688	.3300	.6140	.0418	.758	.370
.568	.3368	.6250	-.0438	.624	.306

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 55° at 0.75 R; Forward

Three-Blade Left-Hand; 53.1° at 0.75 R; Rear

15-Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
2.930	0.1756	0.675	0.0265	3.171	0.762
2.827	.1996	.722	.0197	3.022	.781
2.751	.2182	.756	.0162	2.913	.794
2.692	.2325	.780	.0117	2.830	.802
2.623	.2494	.807	.0087	2.740	.811
2.543	.2674	.831	.0026	2.640	.819
2.422	.2896	.863	-.0062	2.494	.813
2.359	.3005	.875	-.0096	2.423	.809
2.277	.3104	.888	-.0151	2.329	.796
2.225	.3147	.894	-.0204	2.274	.783
2.158	.3182	.897	-.0282	2.203	.766
2.072	.3180	.892	-.0410	2.120	.739
1.950	.3150	.874	-.0487	1.982	.695
1.823	.3138	.863	-.0525	1.878	.663
1.741	.3122	.854	-.0517	1.797	.636
1.665	.3108	.843	-.0522	1.723	.614
1.522	.3080	.831	-.0532	1.580	.564
1.423	.3067	.828	-.0531	1.479	.527
1.331	.3068	.826	-.0527	1.384	.495
1.237	.3063	.827	-.0528	1.287	.458
1.131	.3085	.836	-.0528	1.174	.417
1.017	.3090	.837	-.0532	1.055	.376
.888	.3095	.847	-.0540	.918	.325
.718	.3150	.864	-.0607	.740	.262

TABLE III

Tandem Propellers

Three-Blade Right-Hand; 65° at 0.75 R; Forward

Three-Blade Left-Hand; 62.5° at 0.75 R; Rear

15-Percent-Diameter Spacing

V/nD	C_T	C_P RH+LH	C_P RH-LH	C_s RH+LH	η
3.981	0.2935	1.563	0.0443	3.640	0.747
3.845	.3134	1.594	.0320	3.496	.754
3.759	.3270	1.605	.0236	3.417	.766
3.638	.3450	1.620	.0132	3.304	.775
3.492	.3630	1.622	-.0021	3.171	.782
3.414	.3698	1.628	-.0110	3.097	.775
3.314	.3773	1.623	-.0197	3.010	.771
3.177	.3790	1.598	-.0383	2.888	.754
3.047	.3732	1.559	-.0524	2.789	.729
2.941	.3649	1.516	-.0629	2.707	.708
2.858	.3570	1.470	-.0736	2.653	.694
2.693	.3390	1.409	-.0821	2.519	.648
2.566	.3265	1.354	-.0846	2.412	.620
2.436	.3133	1.298	-.0841	2.309	.587
2.311	.2990	1.247	-.0842	2.215	.554
2.231	.2912	1.221	-.0814	2.145	.532
2.129	.2771	1.179	-.0780	2.061	.500
2.025	.2677	1.155	-.0756	1.969	.470
1.872	.2614	1.122	-.0744	1.833	.432
1.752	.2551	1.115	-.0720	1.717	.404
1.650	.2510	1.108	-.0707	1.617	.377
1.536	.2465	1.100	-.0692	1.511	.344
1.429	.2460	1.100	-.0712	1.404	.322
1.333	.2453	1.093	-.0712	1.311	.299
1.227	.2441	1.092	-.0734	1.208	.274
1.131	.2420	1.090	-.0794	1.113	.251
1.010	.2432	1.102	-.0844	.992	.223

Table III (cont.)

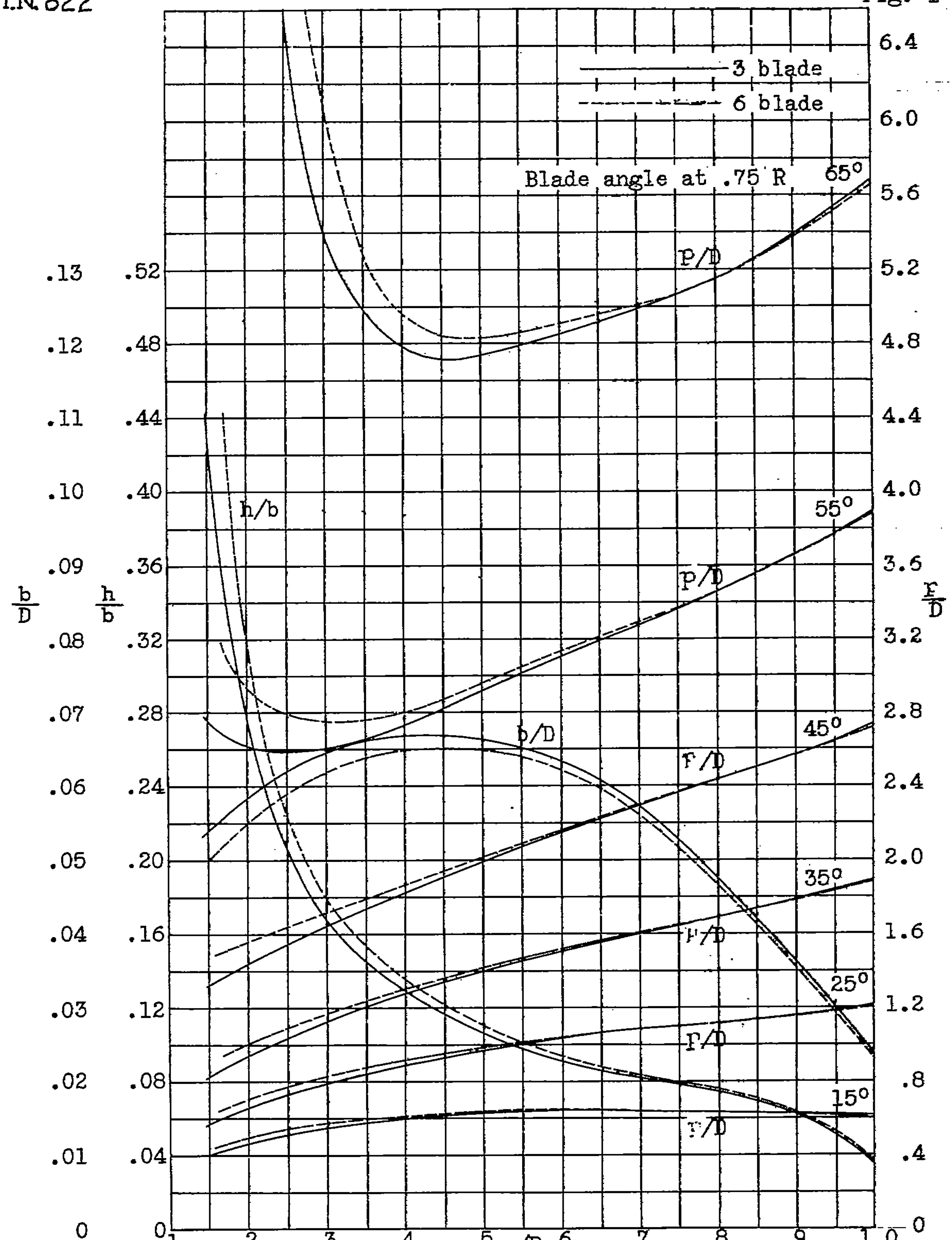

Figure 1.- Blade-form curves. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch.

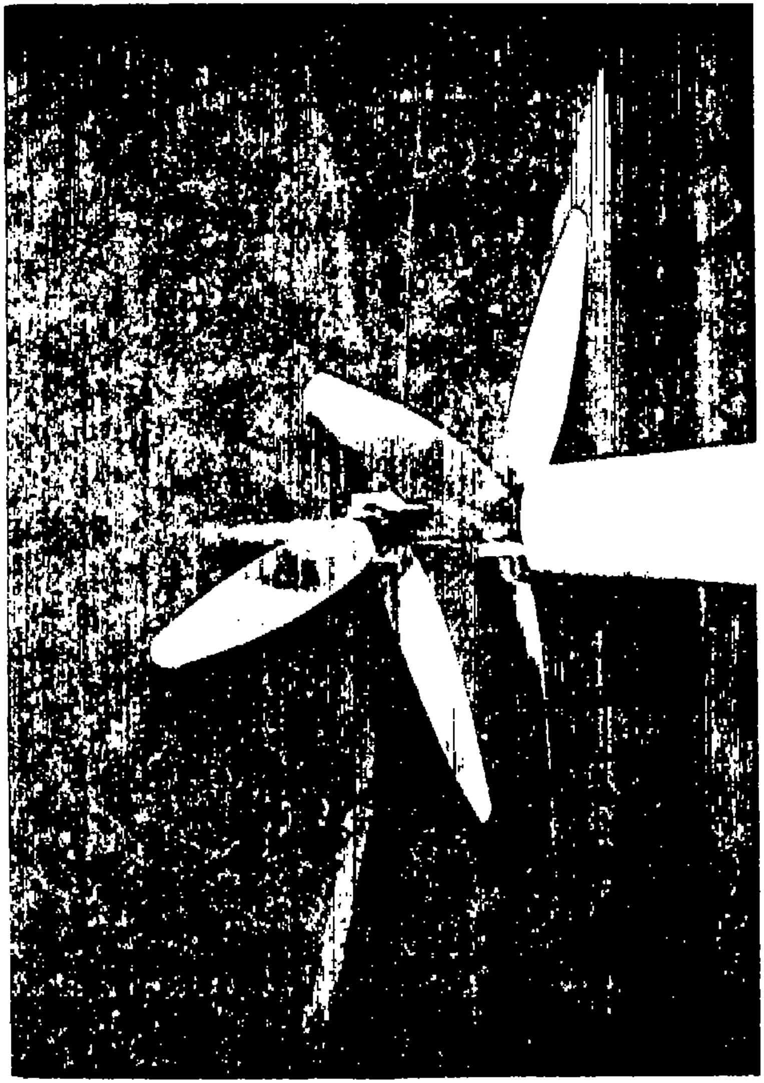

Figure 2.- Three-blade tandem propellers.

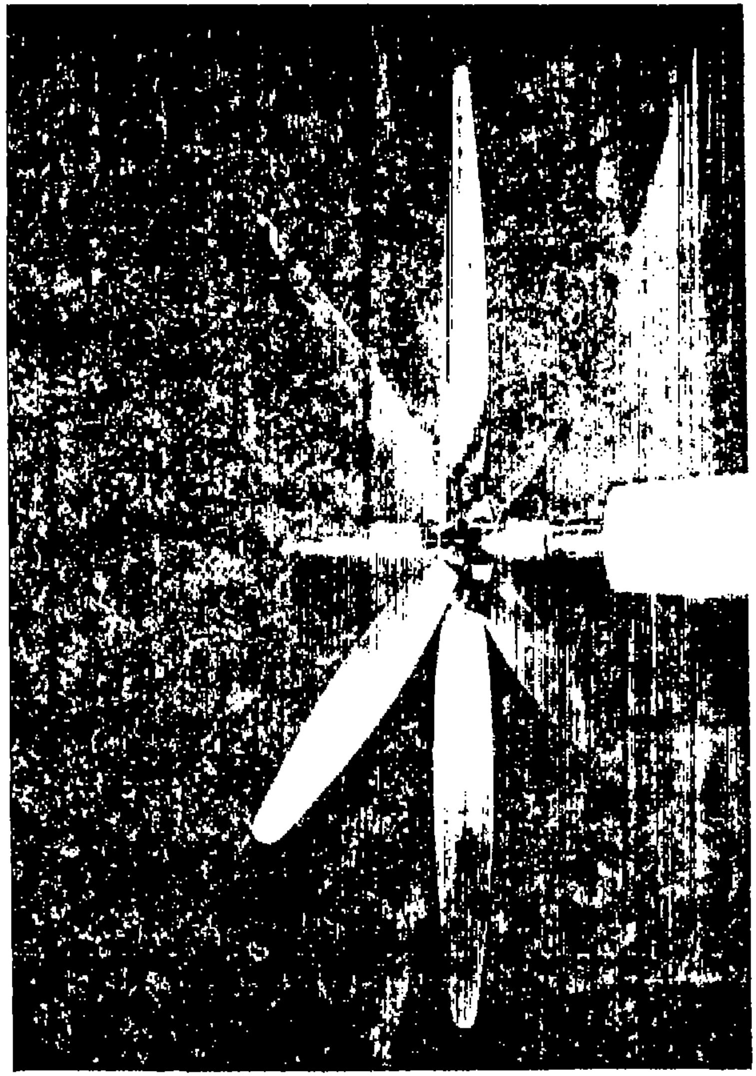

Figure 3.- Six-blade propeller.

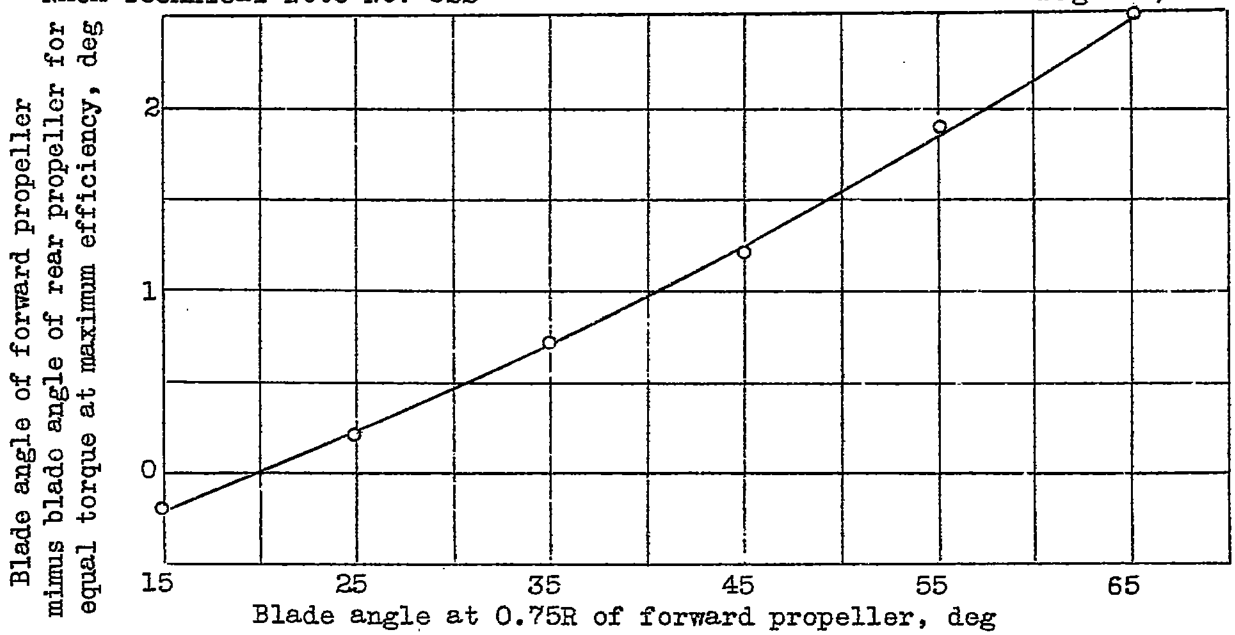

Figure 4.- Difference in blade angles for equal torque at maximum efficiency of tandem propellers.

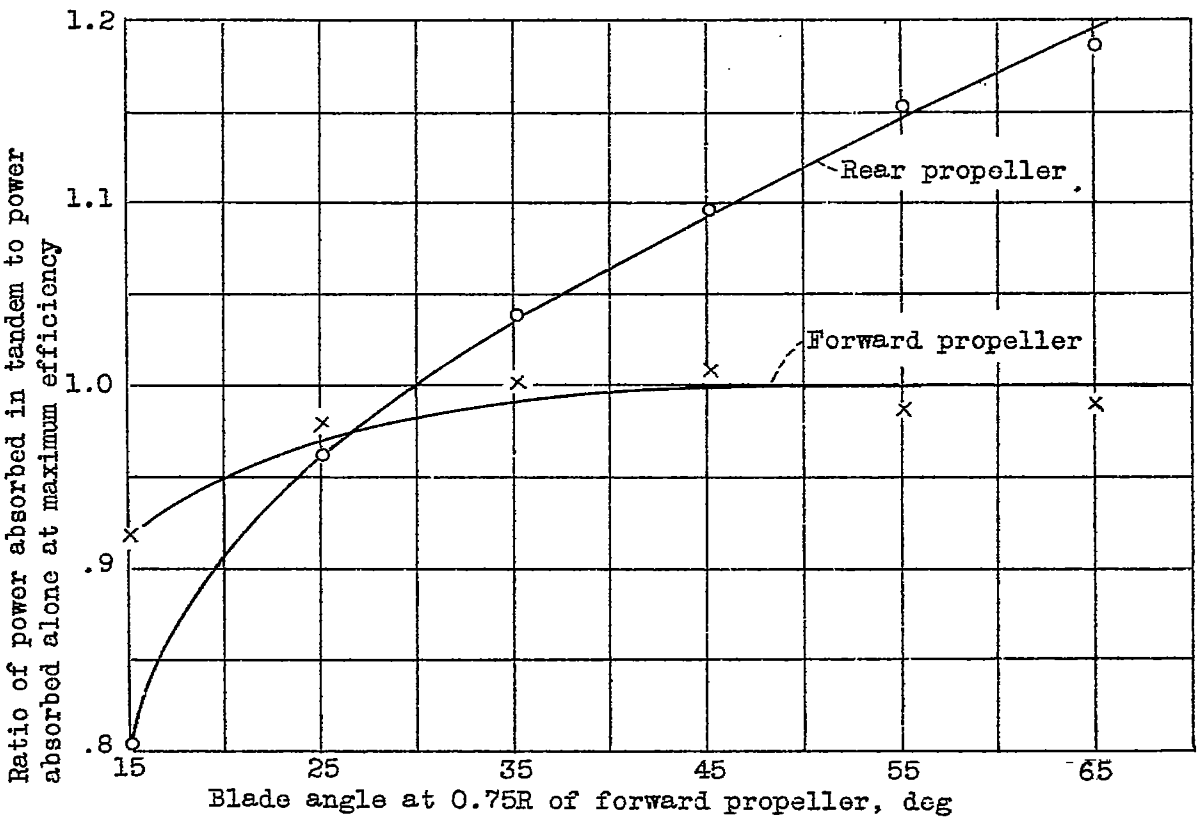

Figure 12.- Effect of each propeller on the other in the tandem combination at maximum efficiency.

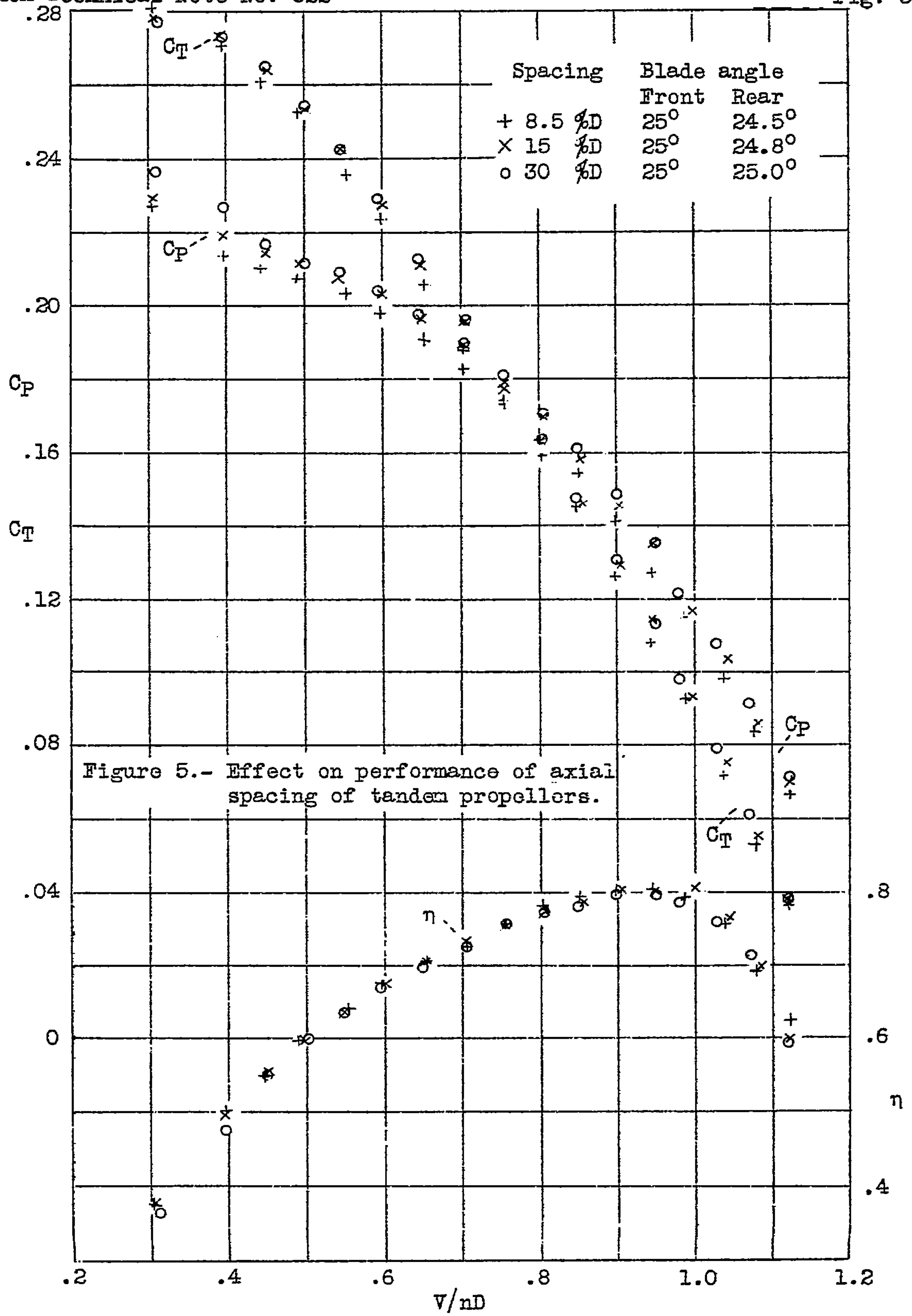

Figure 5.- Effect on performance of axial spacing of tandem propellers.

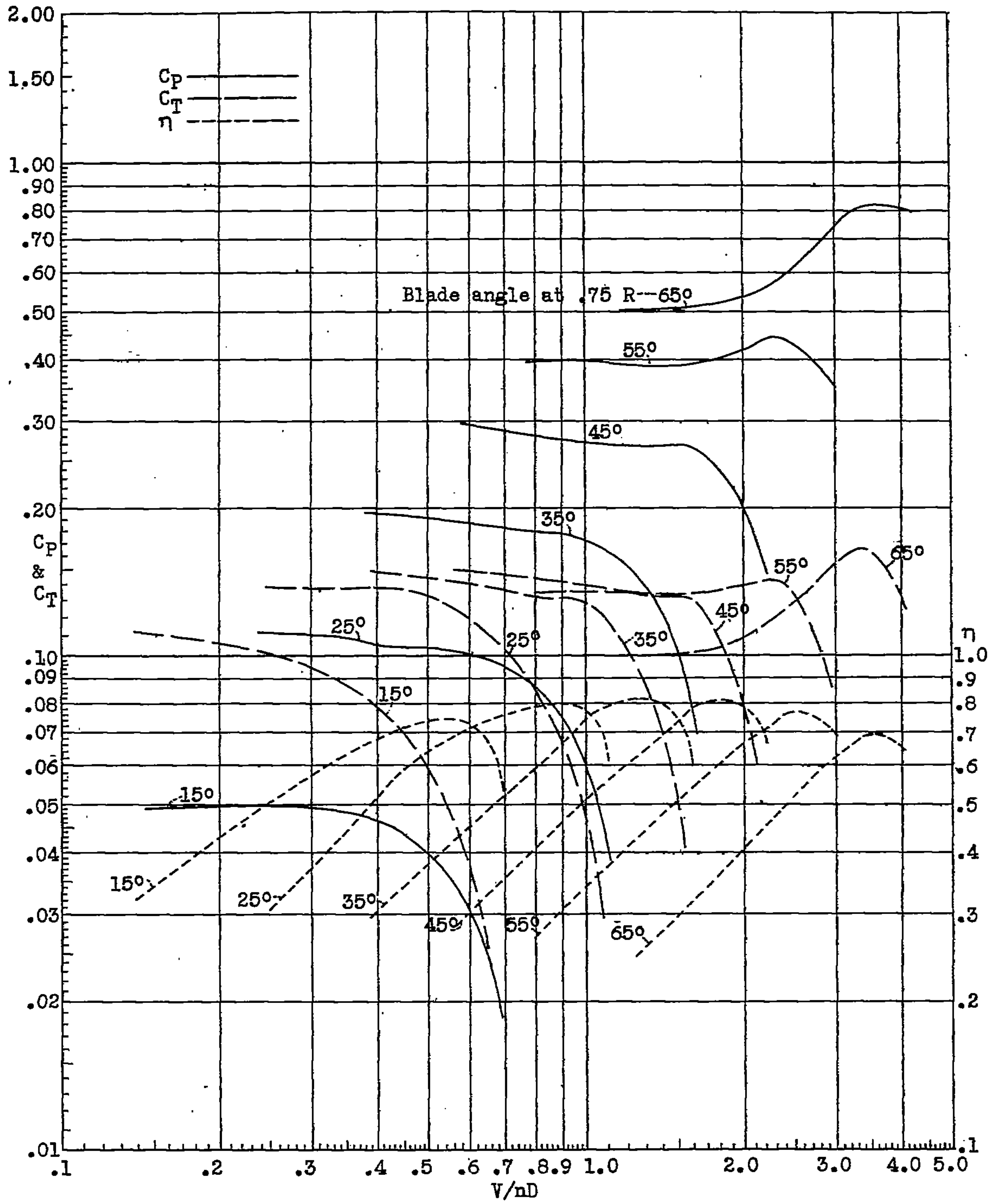

Figure 6.- Thrust-coefficient, power-coefficient, and efficiency curves for three-blade right-hand propeller.

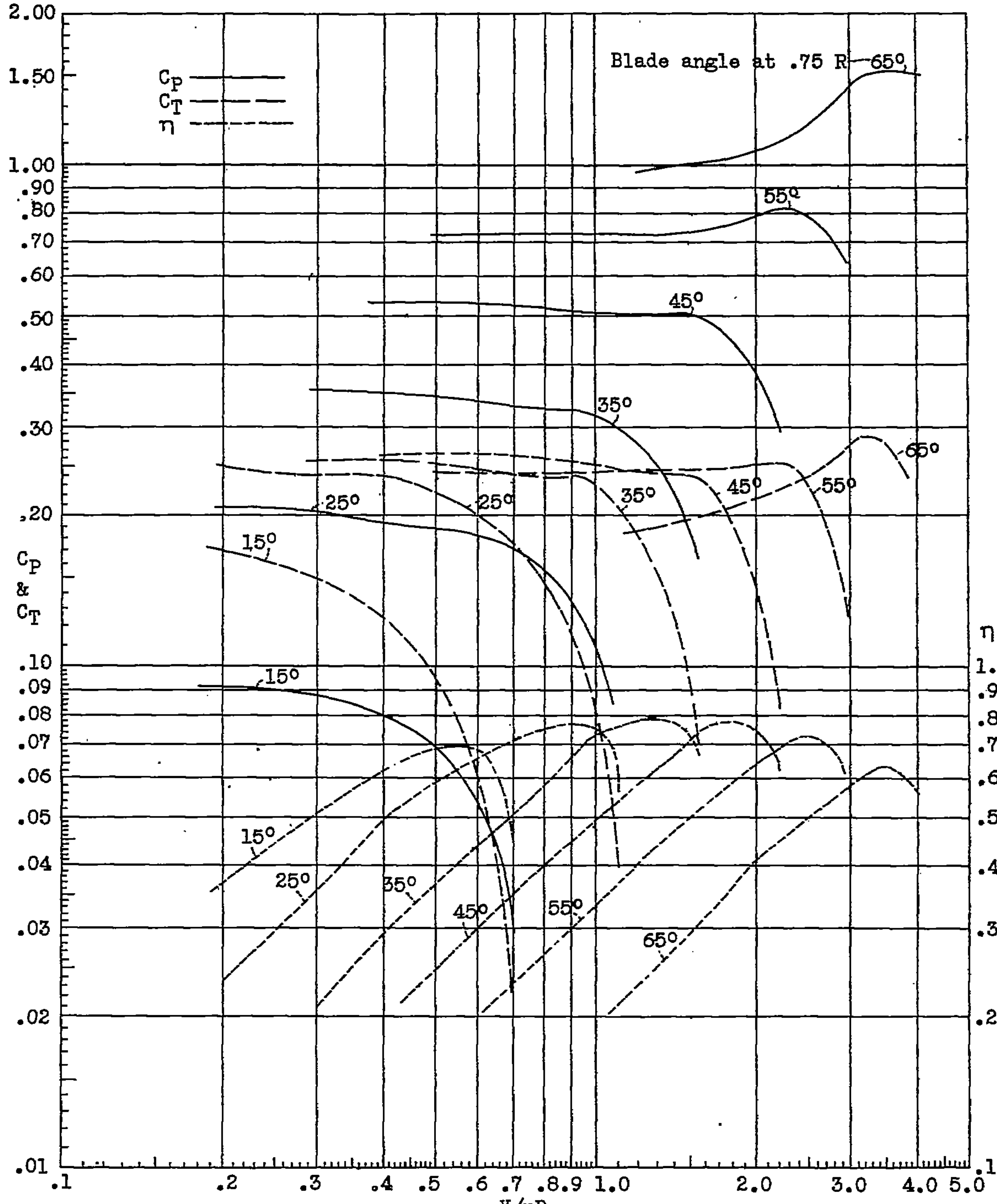

Figure 7.- Thrust-coefficient, power-coefficient, and efficiency curves for six-blade propeller.

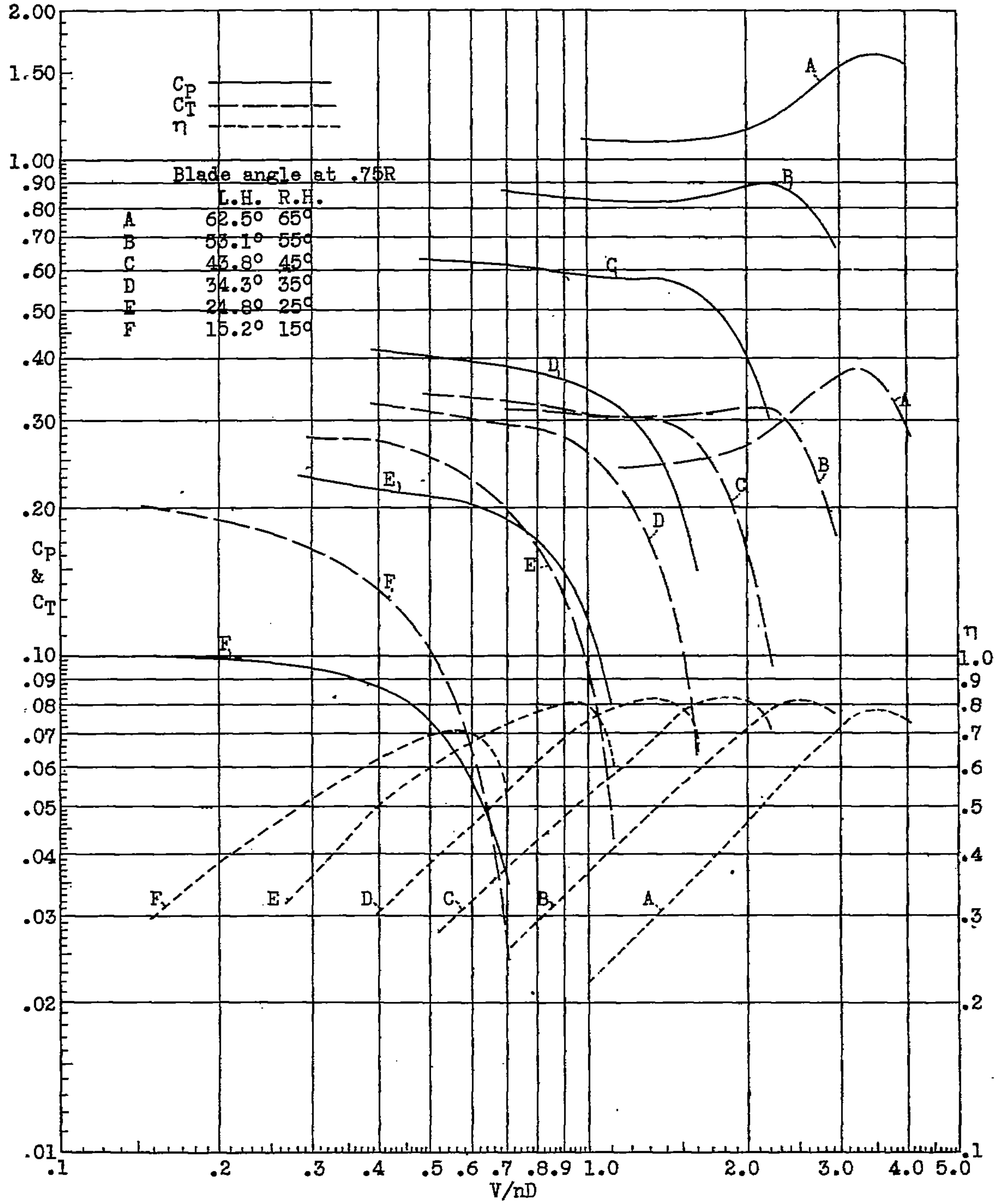

Figure 8.- Thrust-coefficient, power-coefficient, and efficiency curves for three-blade right and left hand tandem propellers.

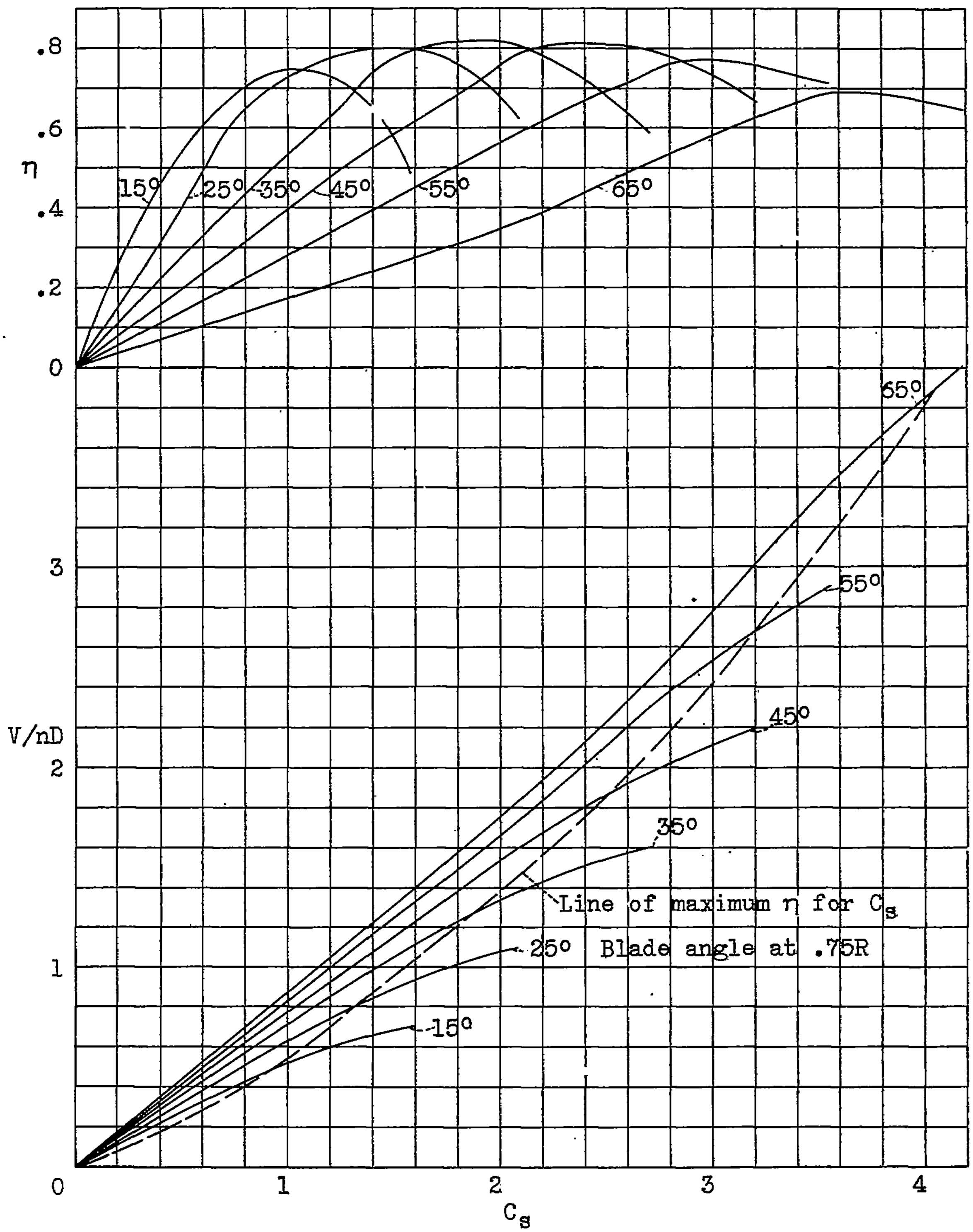

Figure 9.- Design chart for three-blade right-hand propeller.

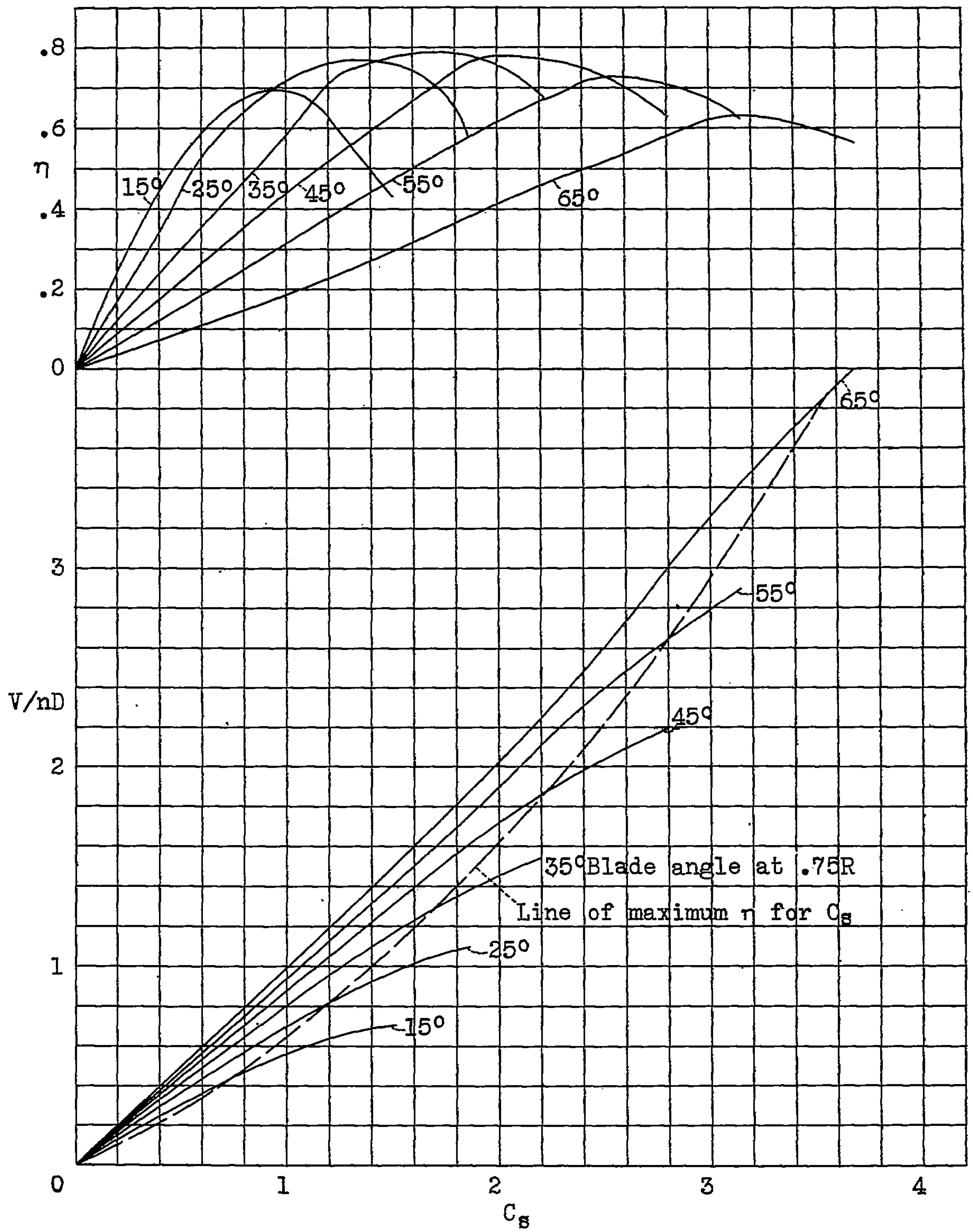

Figure 10.- Design chart for six-blade propeller.

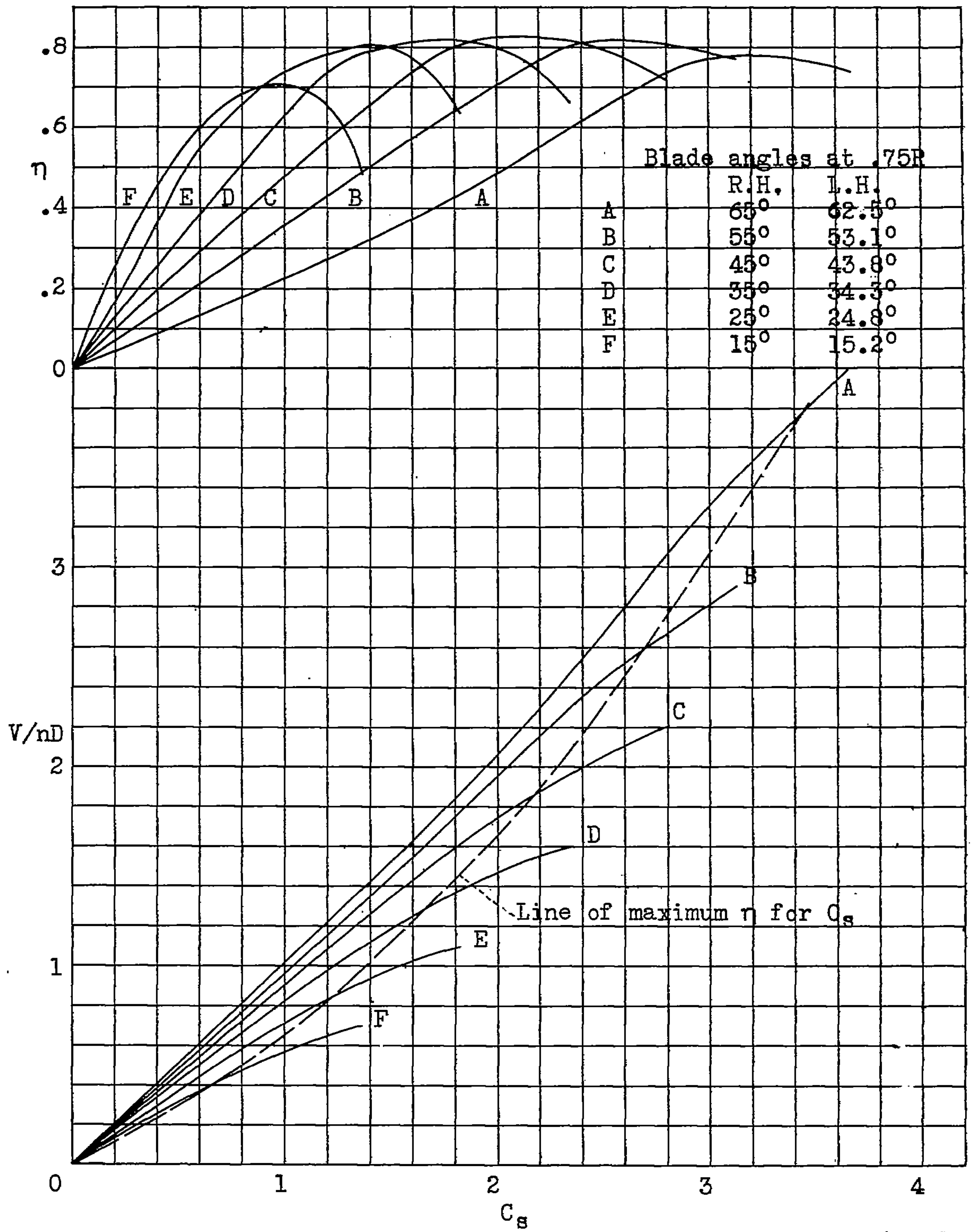

Figure 11.- Design chart for three-blade right and left-hand tandem propellers.

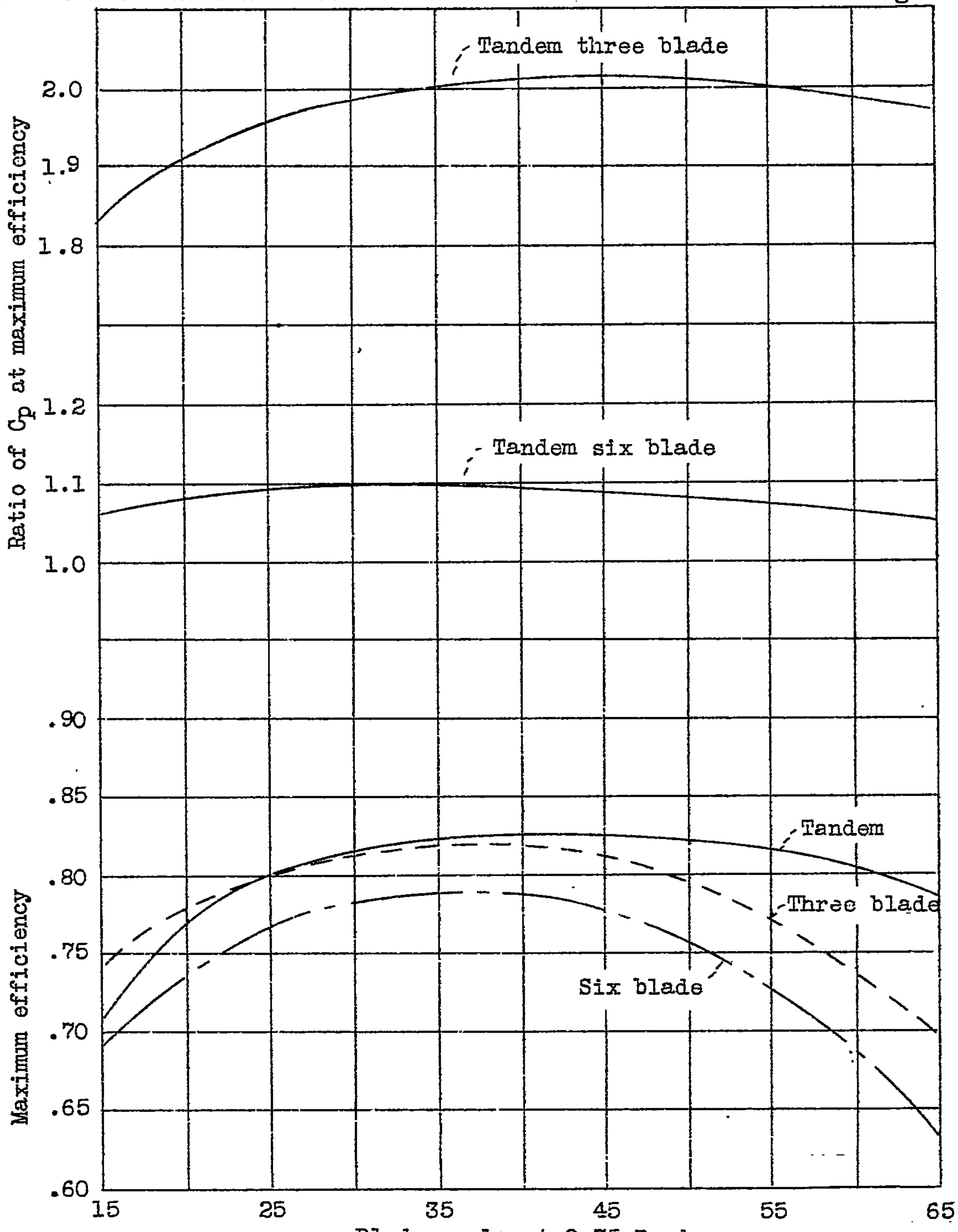

Figure 13.- Summary of results at maximum efficiency.